UNCLASSIFIED
~~RESTRICTED~~

COPY NO.
RM No. E7I25

NACA RM No. E7I25

OCT 11 1948

CLASSIFICATION CHANGED

To UNCLASSIFIED

NACA

Cop. 1

By authority of H. L. Dryden Date 6-11-53
per NACA Release form #1451. By HYR 7-16-53

RESEARCH MEMORANDUM

A COMPARISON OF THE SIMULATED-ALTITUDE PERFORMANCE OF TWO TURBOJET COMBUSTOR TYPES

By Ray E. Bolz, Thomas T. Schroeter
and Eugene V. Zettle

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
October 7, 1948

~~RESTRICTED~~
UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

A COMPARISON OF THE SIMULATED-ALTITUDE PERFORMANCE OF TWO TURBOJET COMBUSTOR TYPES

By Ray E. Bolz, Thomas T. Schroeter
and Eugene V. Zettle

SUMMARY

The performance of a German Jumo 004 can-type combustor and the performance of each of two contemporary turbojet combustors of United States design, an annular type and a can type, were compared to determine whether the Germans had reached an advanced stage in combustor design with the Jumo 004 and to determine whether there are basic, inherent differences in the performance achieved with either the can or the annular type. These comparisons are necessarily both limited in scope and of a transient nature inasmuch as none of the combustors necessarily represents the ultimate design of its type.

The combustors were compared at the same operating conditions of inlet-air temperature, inlet-air pressure, air flow per unit maximum combustor cross-sectional area, and required combustor-outlet temperature as determined from the estimated performance of an existing turbojet engine over the operating range of altitudes and engine rotational speeds. Comparisons were made for two methods of defining the air flow per unit maximum combustor cross-sectional area; namely: (1) the actual maximum cross-sectional area, and (2) the area of an annulus enclosing the cans.

The combustors are compared with respect to altitude operational limits, combustion efficiency, and total-pressure loss across the combustors. Temperature-distribution profiles in the combustor-outlet gases for the three combustors are included, although differences in the test rigs preclude accurate comparison.

Neither of the two United States combustor types showed basic, inherent advantages or disadvantages when compared with each other. The German combustor shows lower altitude operational limits and usually lower efficiencies than the United States combustors. This design under the given conditions of the investigation results in performance that is generally poorer than the United States combustors.

INTRODUCTION

As part of a general program of research on combustors for turbojet engines, the NACA Cleveland laboratory has examined the effect of combustor inlet-air conditions on combustor efficiency and temperature-rise limits (reference 1). Other work has been directed at improving the performance of annular-type turbojet combustors by altering the air passages in the flame tubes or baskets of these combustors and at understanding the effect of design changes on performance in these combustors. Included in this program was an experimental study of the performance of a combustor from a German Jumo 004 engine.

The present investigation is a further contribution to the general subject of the effect of the design of the combustor on its performance. A study was made to compare a German can-type combustor, the Jumo 004, and two United States combustors, a can type and an annular type, with the dual objective of first determining whether the Germans had reached an advanced stage in design with the Jumo 004, and second, of determining whether basic inherent differences exist in the performance achieved with either the can or the annular type. The performance criterions selected were altitude operational limits, combustion efficiency, combustor total-pressure loss, and combustor-outlet temperature distribution. Comparison was made by operating the combustors at conditions simulating inlet-air conditions at zero ram for a reference engine having a compressor-pressure ratio of 4. This procedure established the same inlet-air-temperature and pressure requirements and the same outlet-temperature requirements for all three combustors. The inlet-air weight flow, however, was based on the maximum cross-sectional area of the combustor for the annular combustor; for the can combustor, it was based on (1) the actual maximum cross-sectional area, and (2) on the annular area enclosing the can. The second basis provides a higher air velocity in the can and thus penalizes the can for not using the interstitial space between cans.

The comparison is confined to a limited range of operating conditions and to specific combustor designs and is therefore both transient and incomplete. The data on the two United States combustors do not necessarily coincide with current accomplishments. The data presented, however, will, in general, convey an idea of the relative performance of the various combustor types under typical current altitude operating requirements.

APPARATUS AND PROCEDURE

Combustor Installations

The three combustor types are shown in figure 1. The United States can type exemplifies a type used on a number of American engines and on most of the British engines. The German Jumo 004 can-type combustor has more elaborate air passages than the simple holes and louvers of the United States type. In the Jumo 004, some air enters through swirl vanes, receives a spray of fuel, and burns. The combustion gases then pass through slots to mix with secondary or dilution air. The United States annular combustor shown in figure 1 has two baskets, each equipped with a fuel manifold and a ring of fuel nozzles.

In each test rig, fuel flow was measured by calibrated rotameters, pressures were determined from photographs of manometers, and the temperatures were individually read on indicating potentiometers. AN-F-28 fuel was used in all tests.

United States can type. - The United States can-type combustor studied consists of an outer cylindrical housing, a liner perforated to admit air, a fuel nozzle, and a spark plug. The arrangement of the combustor in the test rig is shown in figure 2. The air flow was measured with a thin-plate orifice installed according to A.S.M.E. specifications; electrical heaters were used to control the inlet-air temperature.

The downstream end of the combustor was connected to an exhaust duct by means of a segment of a simulated turbine-nozzle ring $1\frac{1}{2}$ feet long in order to measure the temperature distribution in the outlet gas at the simulated turbine entrance. The exhaust duct contained water-spray nozzles to cool the outlet gases. For visual inspection of the combustion, two sight windows were installed along one side of the combustor.

The general construction of the temperature- and pressure-measuring instruments located at sections A-A to D-D of figure 2 is shown in figure 3. A tabulation of the number of instruments at each measuring station follows:

	Thermocouples (a)			Total-pressure tubes		Static-pressure taps	
	Station (fig. 2)			Station (fig. 2)		Station (fig. 2)	
	A-A	B-B	D-D	A-A	C-C	A-A	C-C
Number of rakes	-	7	-	3	7	-	-
Probes per rake	-	5	-	3	5	-	-
Total probes	3	35	3	9	35	1	3

[a]The thermocouples were unshielded chromel-alumel junctions.

835

United States annular type. - The annular combustor investigated consists of outer and inner cylindrical housings, an annular liner or basket (double annulus in this case) perforated to admit air, double fuel manifold and fuel nozzles, and two spark plugs. The combustor was installed in a test rig (fig. 4) similar to that described for the United States can-type combustor. The air flow was measured with a variable orifice and the inlet-air temperature was regulated by a fuel-fired preheater in addition to an electrical preheater because of the large quantities of air required by the combustor. In order to provide a uniform air-velocity and air-temperature distribution at the combustor inlet, a plenum chamber and a punched plate were employed in the inlet duct.

The design of the temperature- and pressure-measuring instrumentation at sections A-A to D-D of figure 4 is similar to that shown in figure 3 except that: (1) Different numbers of probes per rake were used; and (2) at the cross section D-D, four shielded thermocouples not shown in figure 3 were used to measure average gas temperature and to check the previous temperature measurements. A tabulation of the number of instruments at each measuring station follows:

	Thermocouples				Total-pressure tubes		Static-pressure taps		
	Station (fig. 4)				Station (fig. 4)		Station (fig. 4)		
	A-A	B-B	C-C	D-D	A-A	B-B	A-A	B-B	C-C
Number of rakes	4	18	4	2	2	4	-	-	-
Probes per rake	4	4	4	2	9	6	-	-	-
Total probes	16	72	16	4	18	24	4	4	1

<u>German Jumo 004.</u> - The Jumo can-type combustor investigated consists of an outer cylindrical housing, a combustion-zone liner, an extension liner, a single upstream-injection fuel nozzle, and a spark plug. The installation in the test rig (similar to that used for the United States can-type combustor) is shown in figure 5. Primary air enters the combustion-zone liner through swirl vanes and the hot combustion gases are directed around a baffle. Portions of the secondary air stream are diverted to cool the combustion-zone liner, including the baffle, and the extension liner before being mixed with the combustion gases. The outlet duct was an ordinary circular duct and hence did not simulate a segment of the turbine nozzle box.

A tabulation of the instruments (with designs similar to those shown in fig. 3) installed at sections A-A to C-C of figure 5 follows:

	Thermocouples			Total-pressure tubes		Static-pressure taps	
	Station (fig. 5)			Station (fig. 5)		Station (fig. 5)	
	A-A	B-B	C-C	A-A	B-B	A-A	B-B
Number of rakes	1	8	1	1	2	-	-
Probes per rake	3	3	6	4	6	-	-
Total probes	3	24	6	4	12	2	4

Procedure

The combustor-inlet conditions and the required combustor- 835
outlet temperature at zero ram pressure of a current turbojet engine with a design compressor-pressure ratio of 4 are presented in figure 6. The combustors were compared on the basis of these data. The increase in air flow based on included area over that based on actual maximum cross-sectional area is 74 percent for the United States can-type combustor and 33 percent for the German combustor.

At each simulated-altitude engine-speed condition, the combustor inlet-air pressure, temperature, and air flow for the particular condition were set and maintained constant while the fuel flow was increased in increments until the average combustor-outlet temperature obtained was either approximately equal to or slightly above the steady-state (zero ram) engine requirements, as given by figure 6, or was the maximum attainable value. Complete data were then recorded at each point. Each point at which the highest attainable combustor-outlet temperature was below the required value was considered to be outside the operational range of altitude and engine speed. Isothermal runs were conducted to determine the frictional-pressure loss.

Calculations

The combustion efficiency is defined in this study as the ratio of the actual rise in total temperature, as obtained from the average of the temperatures measured at the combustor inlet and outlet, to the rise in total temperature theoretically possible as obtained from reference 2 for the fuel-air ratio used; the actual rise in total temperature was measured in each case when the combustor-outlet temperature was set at approximately the required value.

The total pressures represent the averages of the measured total pressures taken at the inlet and the outlet of the combustor.

The following symbols are used in the calculations:

ΔP combustor inlet-to-outlet total-pressure loss, inches mercury q effective inlet dynamic pressure (calculated from maximum cross-sectional area of burner, air flow, and inlet-air density), inches mercury

ρ_1 air density at combustor inlet, pounds per cubic foot

ρ_2 gas density at combustor outlet, pounds per cubic foot

RESULTS AND DISCUSSION

The performance data for the three combustors were examined to provide comparisons of the combustors, especially with regard to altitude operational limits, combustion efficiency, pressure loss, and temperature profile at the combustor outlet.

Because the three combustors were designed for use in different engines, each one was therefore designed for different operating conditions and for use with a different fuel. The selection of a single fuel and a single set of operating conditions (reference engine conditions) may therefore impose unfavorable restrictions on those combustors whose design fuel and design operating conditions differ widely from those selected for the comparison investigations. A tabulation of the specifications for which each combustor was designed is presented in the following table:

Engine type	Maximum thrust (lb)	Engine rotational speed (rpm)	Specific fuel consumption (lb/hr)/(lb thrust)	Dry weight (lb)	Compression ratio	Compressor stages	Air flow per unit maximum cross-sectional area (lb/sec)/(sq ft)	Fuel	Turbine-inlet temperature (°F)
Jumo 004	1950	8,700	1.48	1540	3	8	19.1	[1]J-2	1472
U.S. Annular	3000	12,000	1.07	1150	4	11	18.8	AN-F-28	1500
U.S. Can Type	4000	7,600	1.08	2380	4	11	18.5	AN-F-32	1430

[1]Light Diesel-oil type fuel.

The air flow per unit maximum cross-sectional area was constant for all three combustors in the comparison investigations based on the actual maximum cross-sectional areas of the combustors.

Because the air-flow rates of the reference engine used for setting the operating conditions were the same as those for the annular-type engine listed in the preceding table, it is therefore evident that the Jumo 004 combustor operated at slightly lower than design air velocities and that the U. S. can-type combustor operated at slightly higher than design air velocities.

Altitude Operational Limits

Actual maximum cross-sectional area. - The altitude operational limits of the three combustors with air flows based on actual maximum cross-sectional areas are shown in figure 7 and compared in figure 8 as plots of altitude against engine rotational speed. The figures show the higher altitude operational limits of the two United States combustors compared with that of the German, which appears definitely inferior on this basis. The altitude limits of the United States can-type combustor are higher than those of the United States annular type at engine speeds above 6500 rpm and are lower at engine speeds below 6500 rpm for the operating conditions of the reference engine.

Included annular cross-sectional area. - The altitude operational limits of the two can-type combustors with air flows based on included annular areas are shown in figure 9 and compared in figure 10 with the curve for the United States annular-type combustor, as obtained from figure 7. The curves show an operating advantage of approximately 15,000 feet for the United States annular type at engine speeds of about 4000 rpm and nearly equivalent limits for the United States can and annular types at engine speeds above about 7000 rpm. The low altitude operational limits shown in figure 9(a) as compared with those of figure 7(a) for the United States can-type combustor are a reflection of the increased air velocities imposed on the can-type combustors by basing the air flow on the included annular area. Figure 9(b) indicates that the higher air velocities imposed on the German Jumo 004 combustor in this study cause almost complete altitude failure of the unit and reduces the altitude operational limit at an engine speed of 6000 rpm by more than 15,000 feet below that shown in figure 7(c). The curve shown in figure 9(b) could not be extended to higher engine speeds because the altitude limit for engine speeds above about 6000 rpm was below 10,000 feet and the experimental conditions exceeded the range of the test equipment.

Combustion Efficiency

Actual maximum cross-sectional area. - Lines of constant combustion efficiency (ratio of actual to theoretical total-temperature rise) for air flows based on actual maximum cross-sectional area are plotted for each combustor on altitude-engine speed coordinates in figure 11. The lines of constant combustion efficiency have the same general shape as the curves of the altitude operational limits. The values of combustion efficiency vary from about 95 percent at low altitudes to approximately 40 percent at altitudes approaching the operational limits. Figure 12 (cross-plotted from fig. 11) shows the variation of combustion efficiency with altitude at various engine speeds. Figures 11 and 12 indicate that for the actual-area comparison the United States annular type exhibits the highest values of combustion efficiency among the three combustors at altitudes below 55,000 feet at 11,000 rpm and below 40,000 feet at 8000 rpm; the United States can-type combustor exhibits highest efficiencies above these altitudes up to the operational limits, although the difference in efficiency between these two combustors is less than 10 percent over the range of conditions investigated. For the German Jumo 004 combustor, combustion efficiencies at 7000 rpm are comparable with those of the United States can-type combustor at 8000 rpm; however, at 11,000 rpm the values are from 1 to 15 percent lower, the low efficiencies occurring at high altitudes.

Included annular cross-sectional area. - For comparison of the combustors at air flows based on included annular area, lines of constant combustion efficiency for the United States can-type combustor are plotted on altitude-engine speed coordinates in figure 13. Figure 14 shows the variation of combustion efficiency with altitude for the two United States combustors at engine rotational speeds of 11,000 and 8000 rpm. The United States can-type combustor has considerably lower combustion efficiencies below the altitude operational limit than the United States annular-type combustor; the difference is at least 30 percent for low-speed, low-altitude operation. The low combustion efficiencies for the United States can-type combustor in figure 14 as compared with those in figure 12 indicate the effect of the 74-percent increase in the velocity of air entering the combustor as a result of basing the air flow on the included annular area. Combustion efficiencies for the German Jumo 004 combustor were not plotted because of the limited range over which this combustor was operable under the included-area conditions.

Pressure Loss

The total-pressure-loss data are presented in figure 15 in a correlation of $\Delta P/q$ (the ratio of total-pressure loss to effective inlet dynamic pressure) plotted against the ratio of the inlet density to the outlet density ρ_1/ρ_2 for each of the three combustors; a straight line is obtained in each case. The results indicate that the United States can-type combustor has a 10 percent lower frictional- (isothermal) pressure loss than the United States annular type, but has a higher momentum loss, which results in about a 16 percent larger over-all pressure loss at a density ratio of 3.0. At a density ratio of 3.0, the Jumo 004 combustor has a pressure drop that is about 19 percent less than the pressure drop for the United States can-type combustor.

Temperature Profile at Combustor Outlet

Figures 16 to 18 present two representative combustor-outlet temperature profiles for each of the three combustors studied based on air flows for actual maximum cross-sectional-area comparison. Figure 19 presents two additional profiles for the United States can-type combustor with an air flow based on included annular area. The profiles correspond to test runs at an engine rotational speed of 11,000 rpm and at both (1) the lowest altitude tested and (2) either the altitude immediately below the operational limits or the highest altitude tested.

The figures for the actual maximum cross-sectional area (figs. 16 to 18) show a rather severe temperature profile especially at the high altitude for the United States annular-type combustor compared with the profile of the United States can type even when only a sector of the annular combustor is considered. The temperature profiles for the German Jumo 004 combustor indicate more severe variations than those for the United States can-type combustor; however, any comparison is difficult because only single cans from multican combustors were tested and the shape of the outlet ducting for the German Jumo 004 combustor did not simulate a section of the turbine-nozzle ring.

For the United States can-type combustor, figure 19 indicates a larger variation in the temperatures of the outlet gases under included annular-area conditions than under actual maximum cross-sectional-area conditions as a result of increased air and fuel flow through the combustor under the included annular-area conditions.

All factors considered, the data of this study indicate that no basic inherent advantages or disadvantages appear to be associated with either of the two United States combustor types investigated.

SUMMARY OF RESULTS

A comparison of the simulated-altitude performance of United States annular- and can-type combustors and a German can-type combustor with inlet-air conditions and outlet-temperature requirements for a reference turbojet engine indicated that:

1. The German Jumo 004 can-type combustor with air flows based on actual maximum cross-sectional areas operated, in comparison with a United States can-type combustor, at: (a) lower combustion efficiencies for high-speed, high-altitude operation but at comparable efficiencies at low speeds; (b) lower altitude operational limits over the entire range of engine speeds investigated; and (c) about a 19 percent lower total-pressure loss during combustion than that for the United States can-type combustor.

2. With air flows based on the actual maximum cross-sectional areas, the United States can-type combustor operated, in comparison with the United States annular type, at: (a) comparable values of combustion efficiency (within 10 percent over the range of conditions investigated); (b) higher altitude operational limits at engine rotational speeds above 6500 rpm (lower limits below 6500 rpm); and (c) about a 16 percent higher total-pressure loss with combustion.

3. The German Jumo 004 combustor, above engine rotational speeds of 6000 rpm with air flow based on the included annular area, was inoperative at altitudes that could be simulated in the test rig (10,000 ft).

4. With air flows based on the annular cross-sectional area included by the cans, the United States can-type combustor exhibited values of combustion efficiency from 0 to at least 30 percent lower than the United States annular type. Altitude operational limits were comparable to those for the annular combustor at engine speeds above 7000 rpm and were as much as 15,000 feet lower at lower engine speeds.

5. No basic inherent advantages or disadvantages appeared to be associated with either of the two United States combustor types investigated.

Lewis Flight Propulsion Laboratory, 835
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Childs, J. Howard, McCafferty, Richard J., and Surine, Oakley W.: Effect of Combustor-Inlet Conditions on Performance of an Annular Turbojet Combustor. NACA TN No. 1357, 1947.

2. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN No. 1086, 1946.

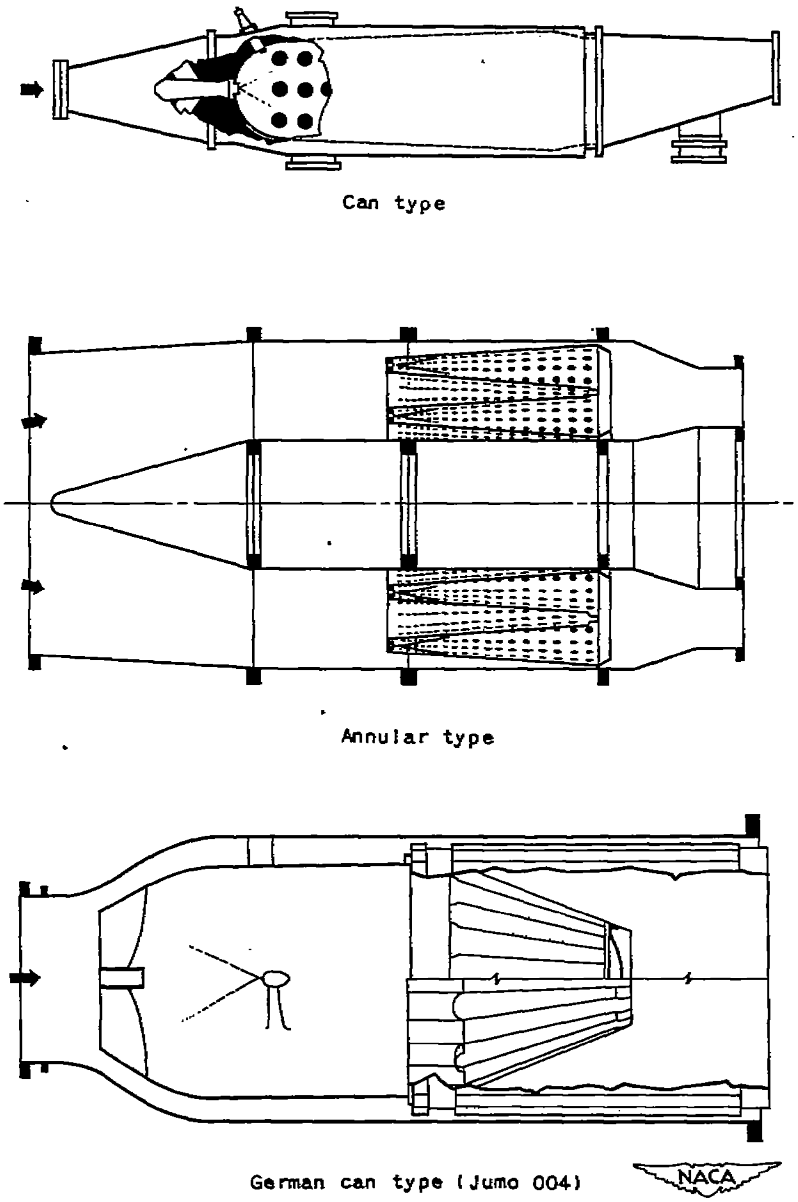


Figure 1. - Sketches of turbojet combustors.

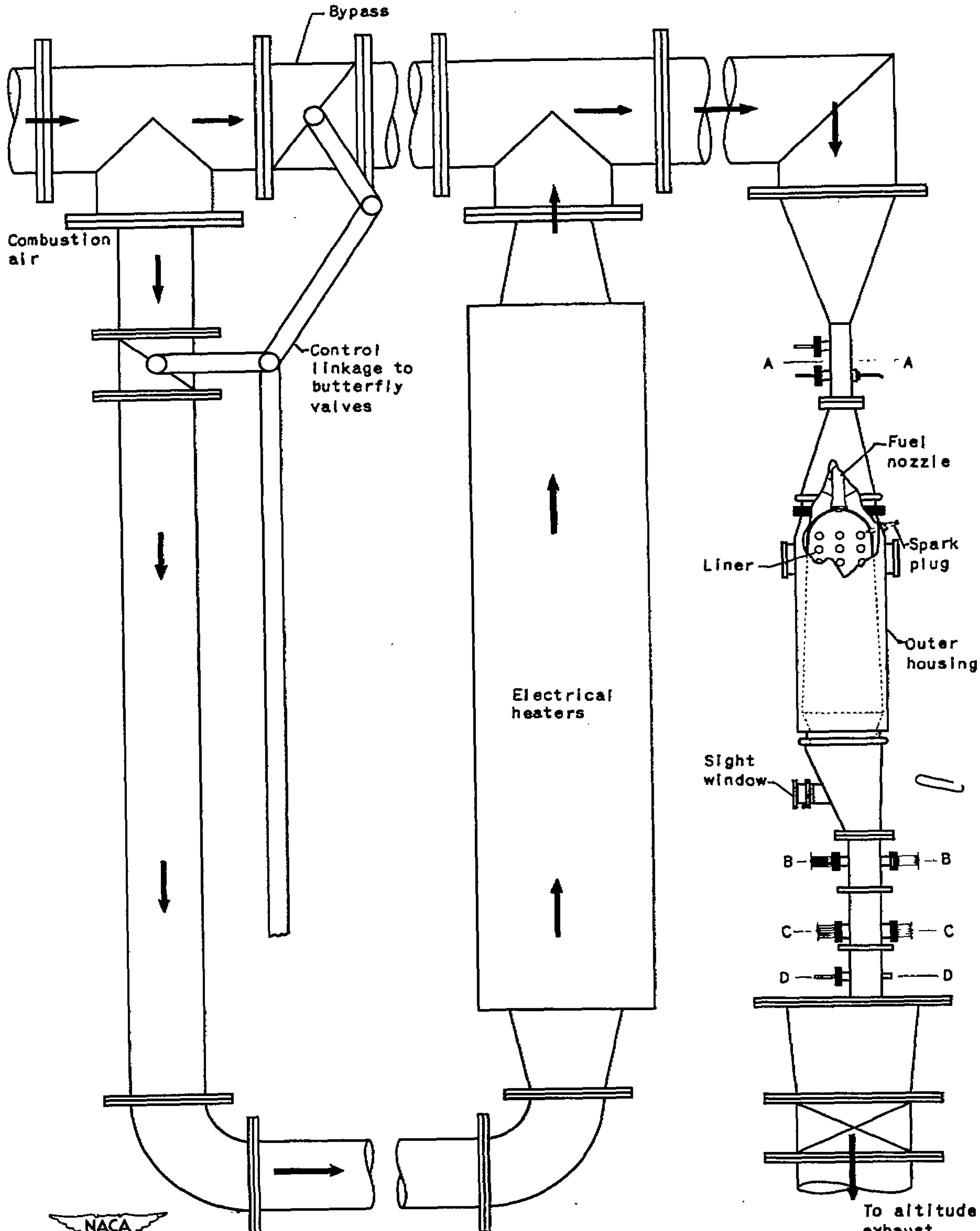


Figure 2. - Schematic sketch of U. S. can-type combustor installed in test rig.

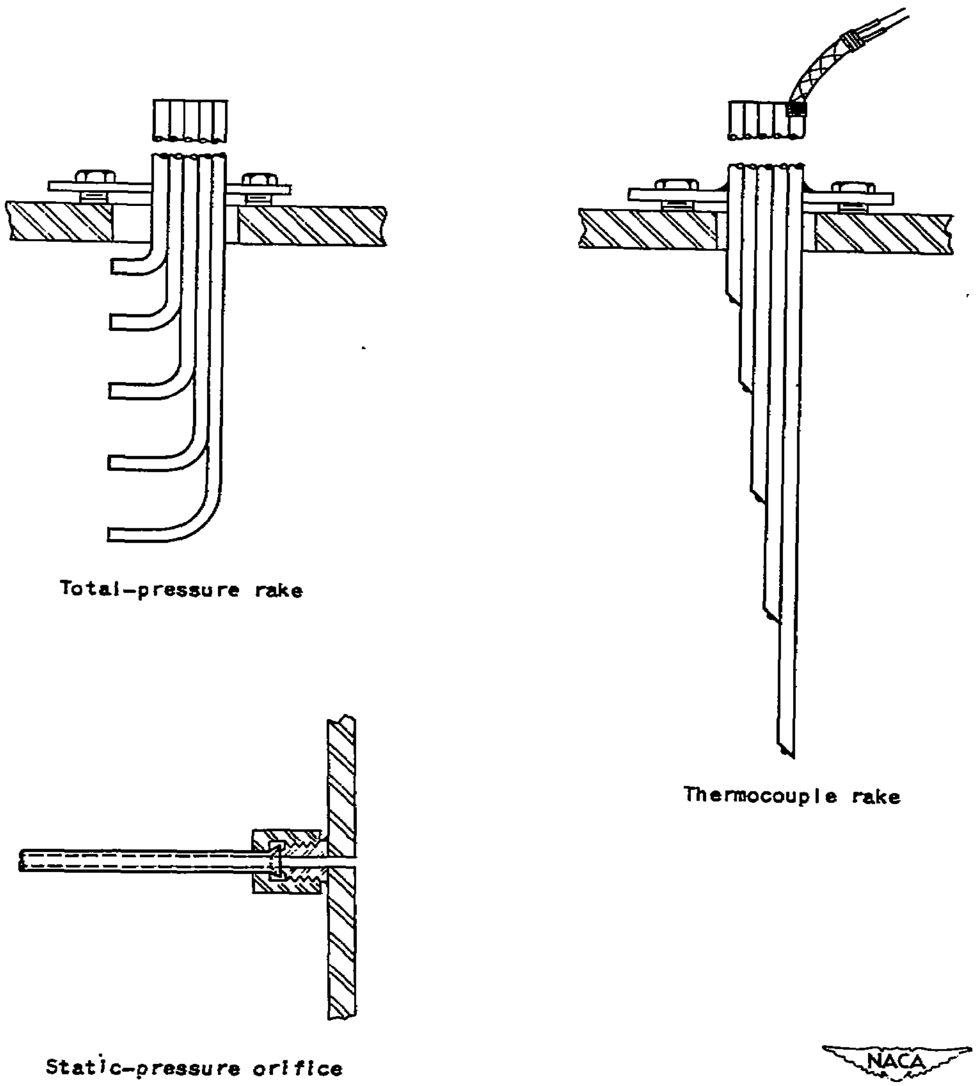


Figure 3. - Typical instruments used in combustor investigations.

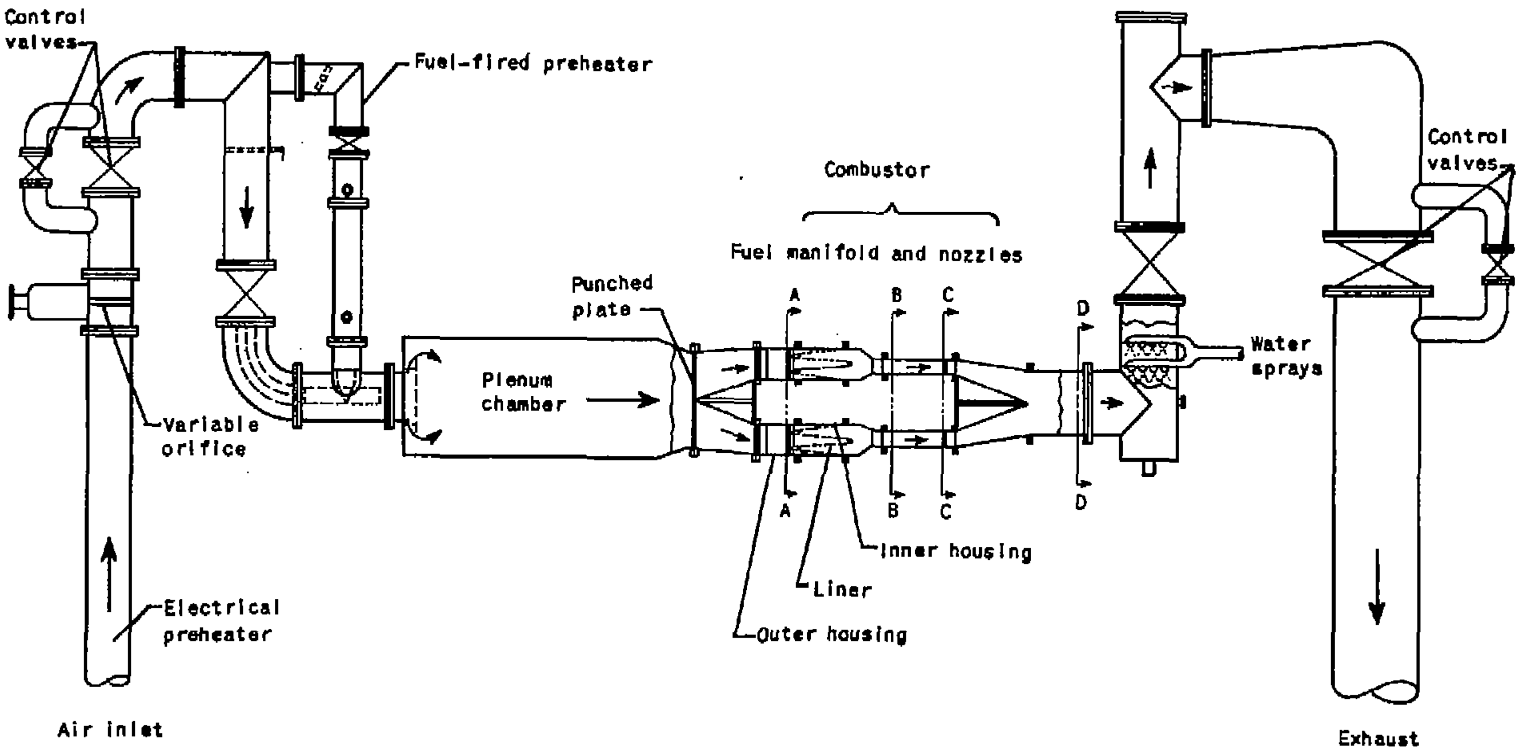


Figure 4. - Schematic sketch of U. S. annular-type combustor installed in test rig.

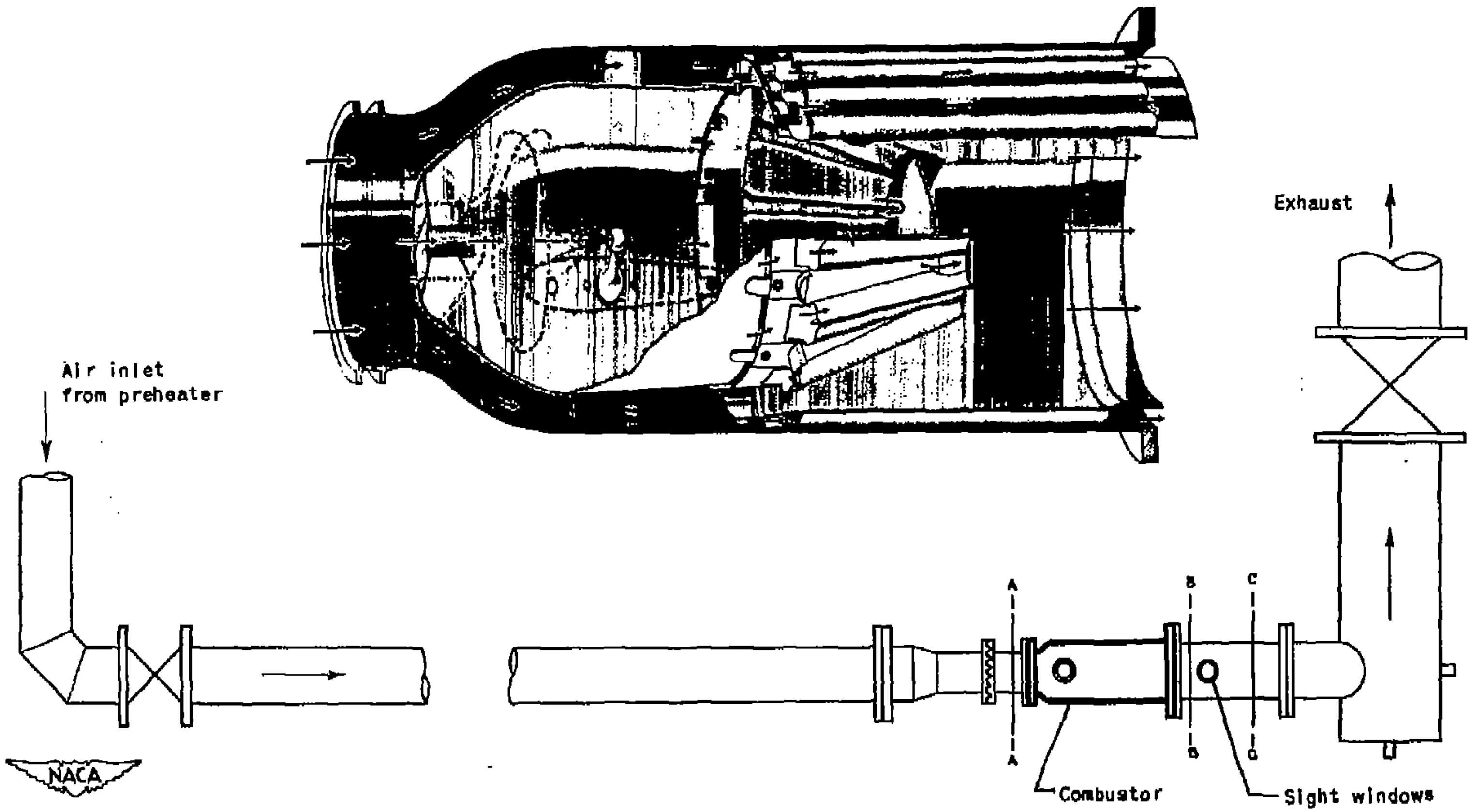
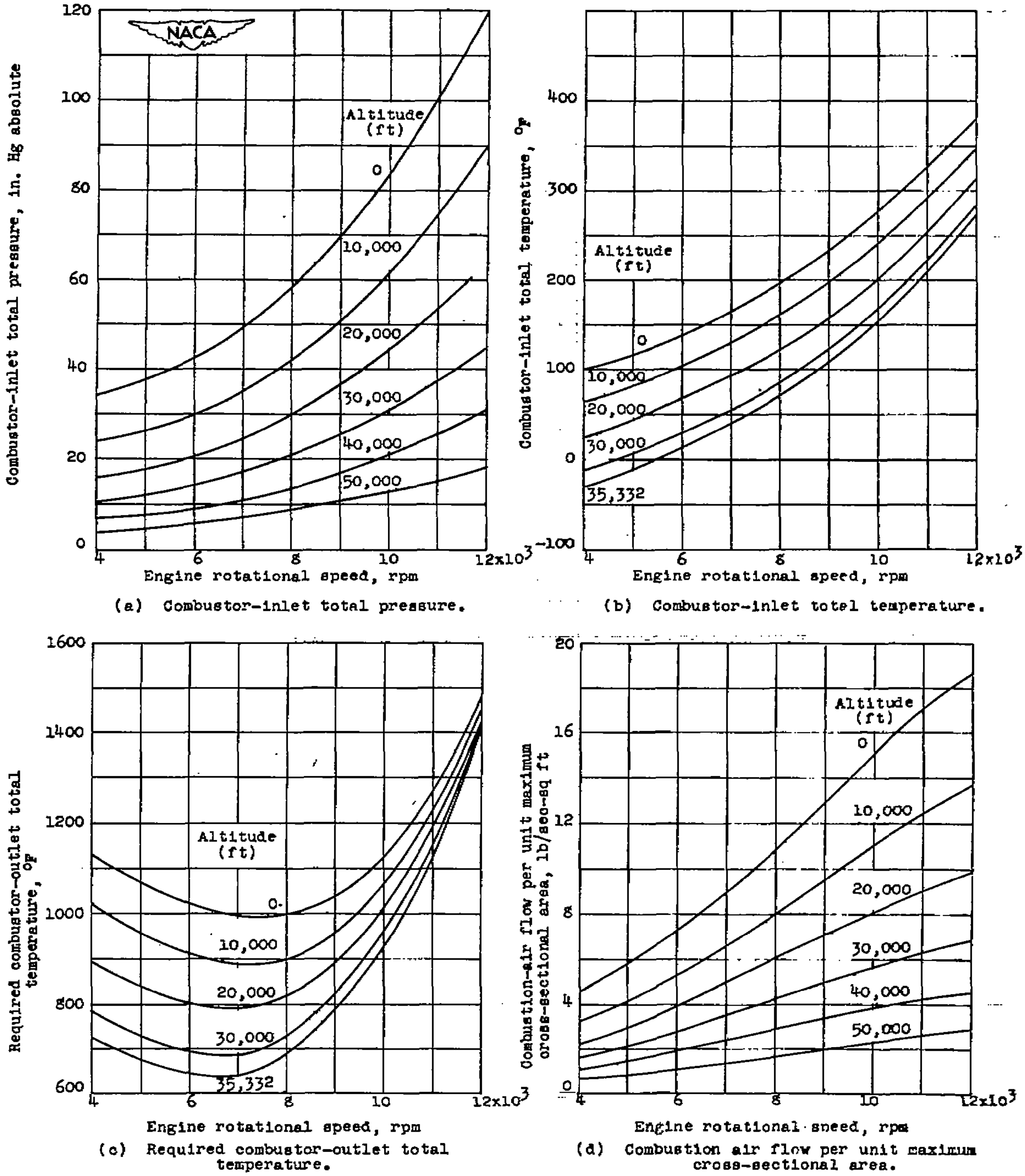


Figure 5. - Schematic sketch of German Jumo 004 can-type combustor and test-rig installation.



(a) Combustor-inlet total pressure.

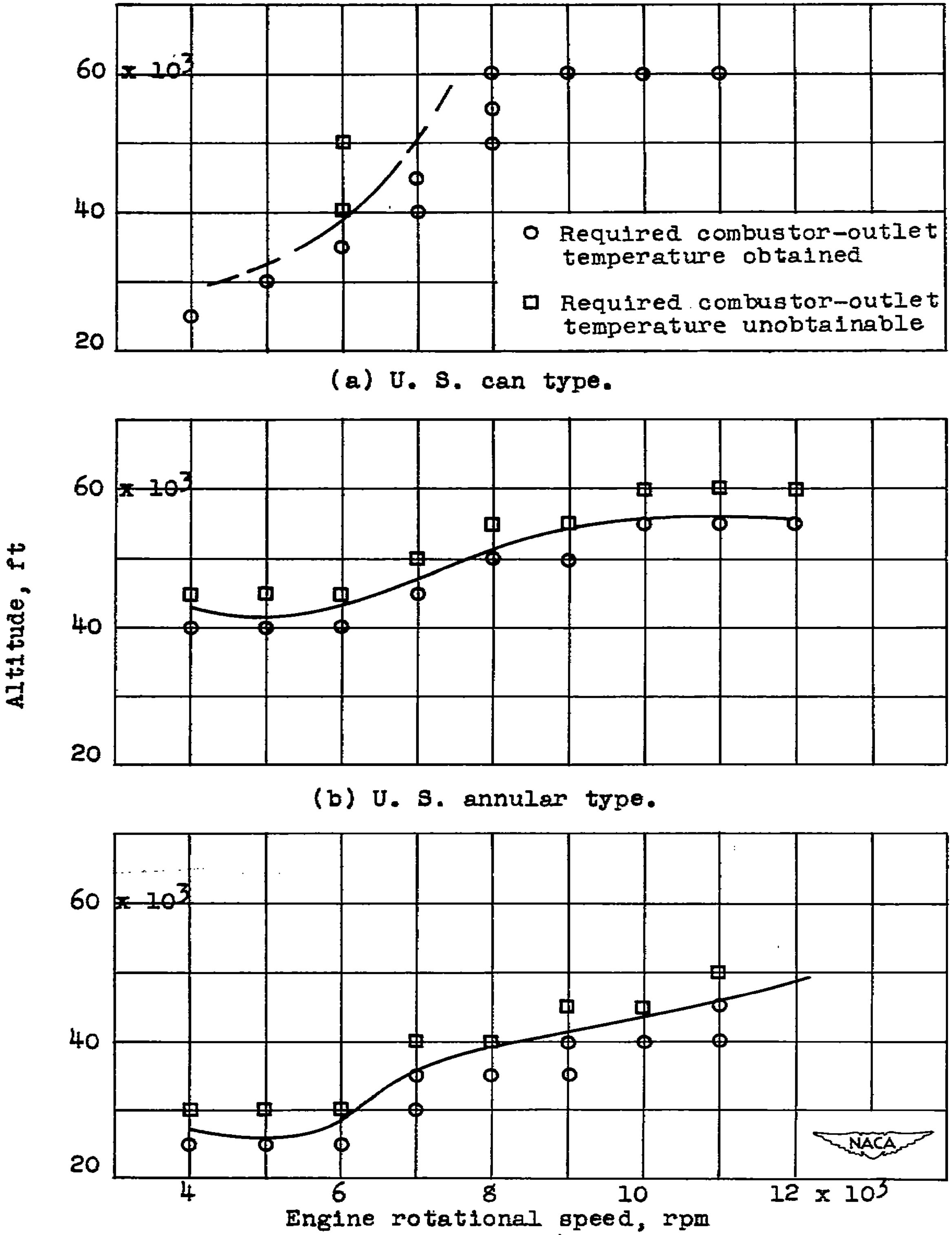
(b) Combustor-inlet total temperature.

(c) Required combustor-outlet total temperature.

(d) Combustion air flow per unit maximum cross-sectional area.

Figure 6. – Variation of combustor operating conditions with engine speed for various altitudes based on performance of reference turbojet engine. Flight speed, 0 mile per hour; compressor-pressure ratio, 4.

835



(c) German Jumo 004 type.

Figure 7. – Altitude operational limits of combustors with air flows based on actual maximum cross-sectional areas.

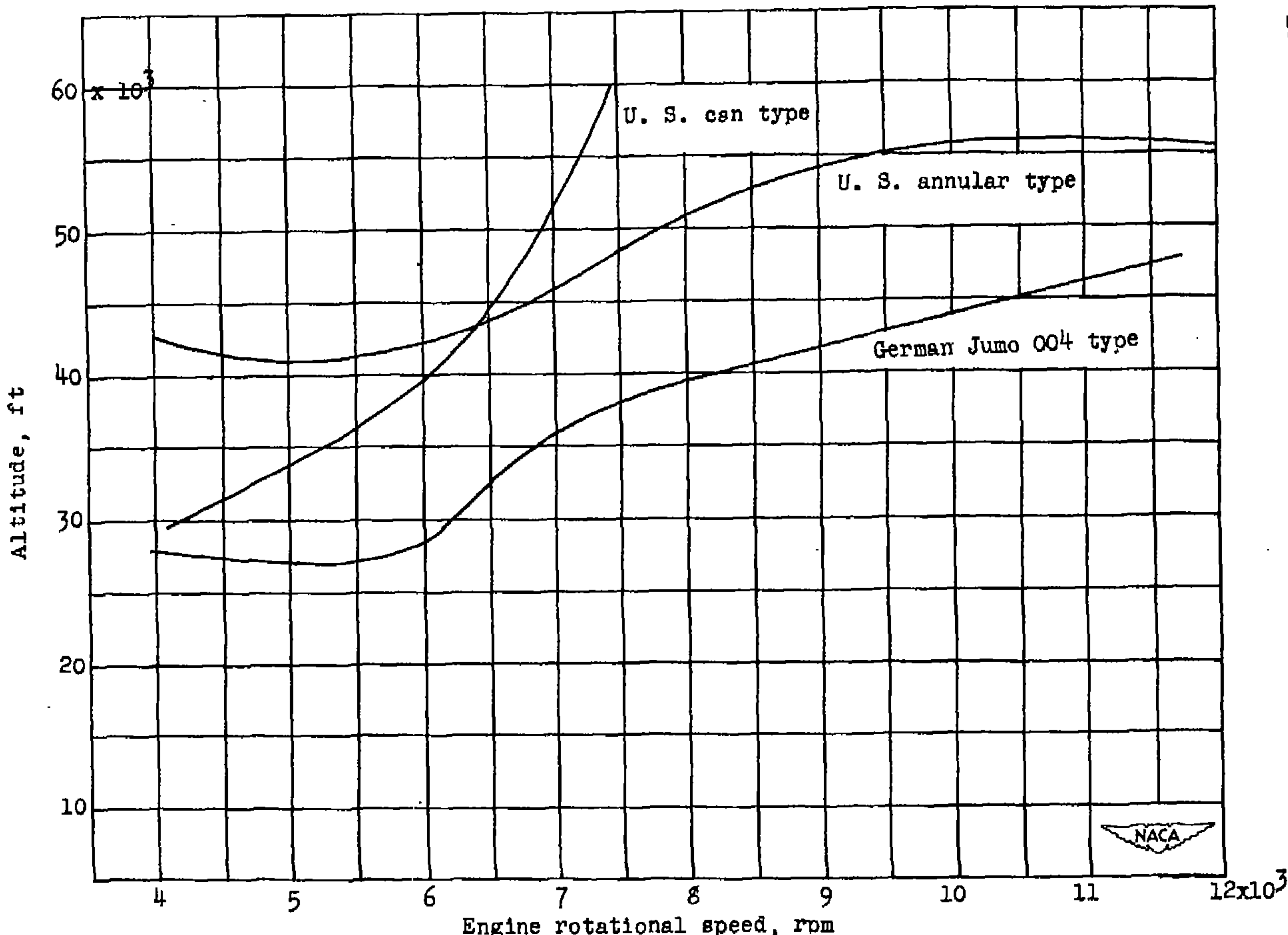
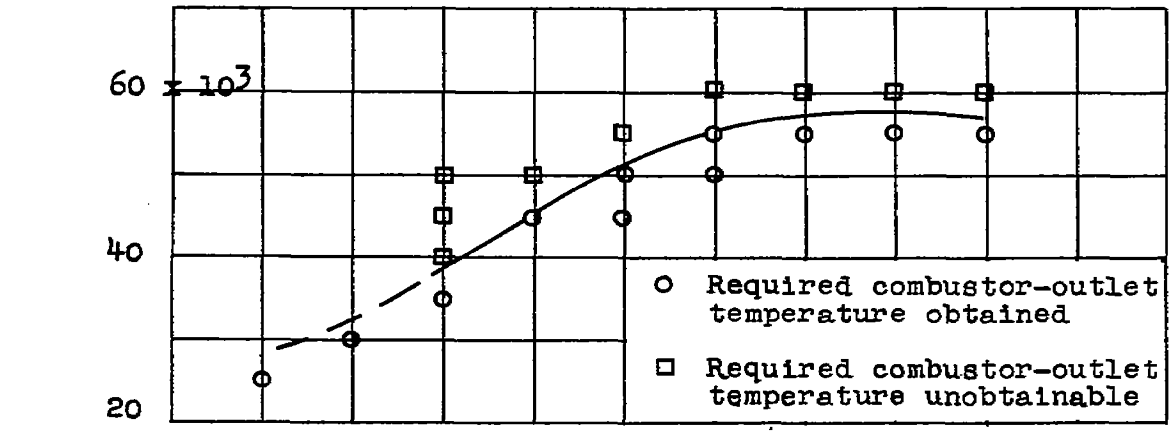
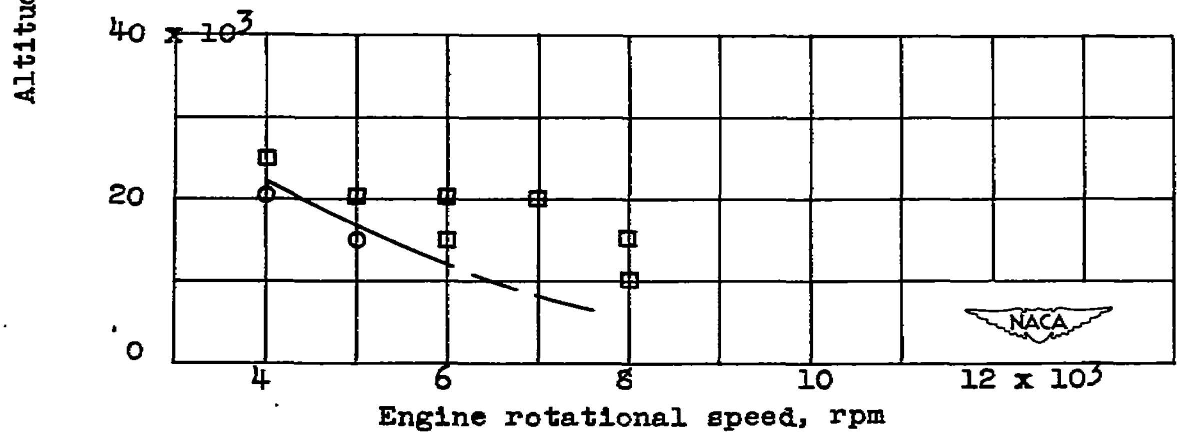


Figure 8. - Comparison of altitude operational limits of combustors with air flow based on actual maximum cross-sectional areas.

835



(a) U. S. can type.



(b) German Jumo 004 type.

Figure 9. - Altitude operational limits of can-type combustors with air flows based on included annular areas.

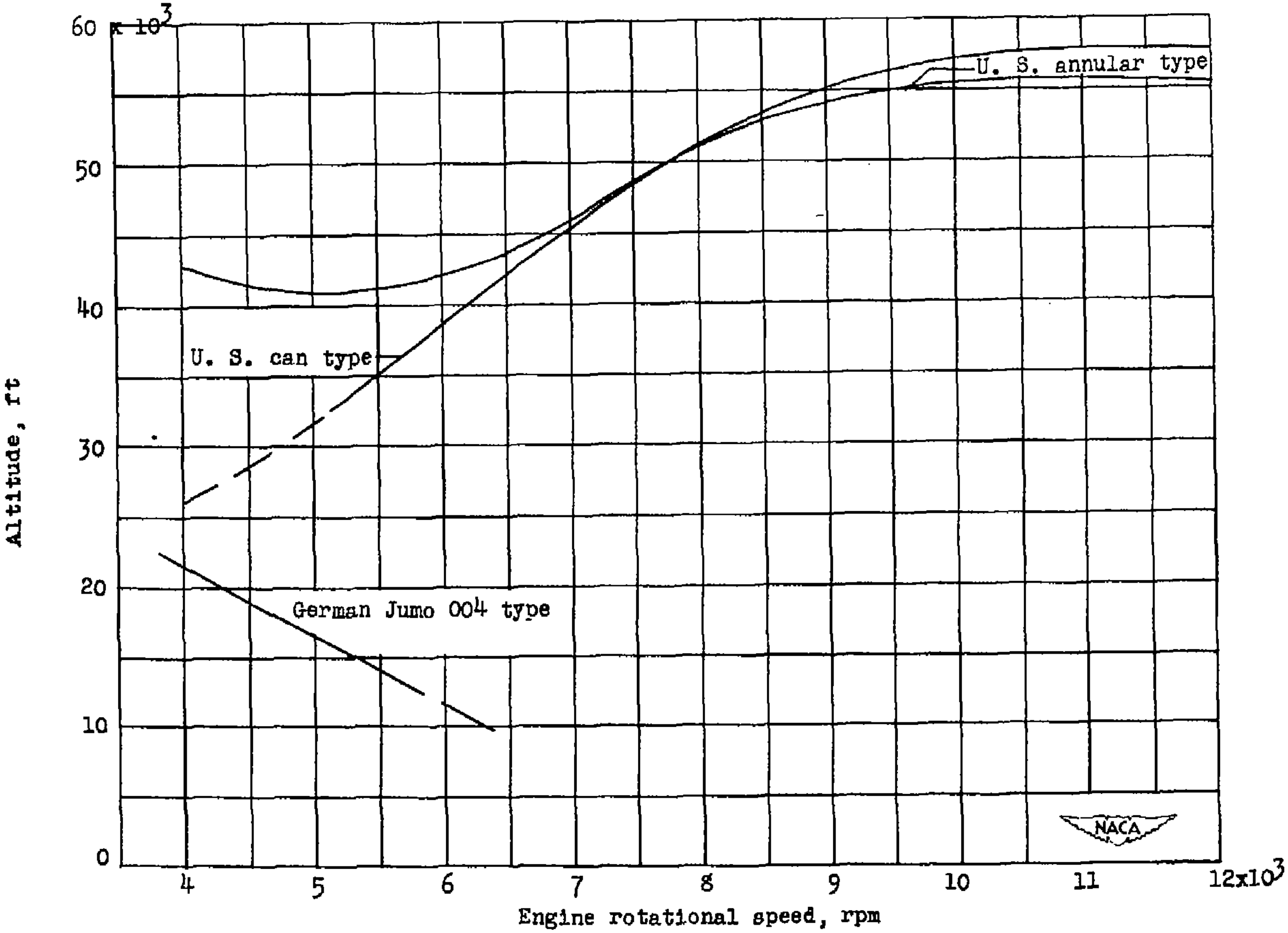
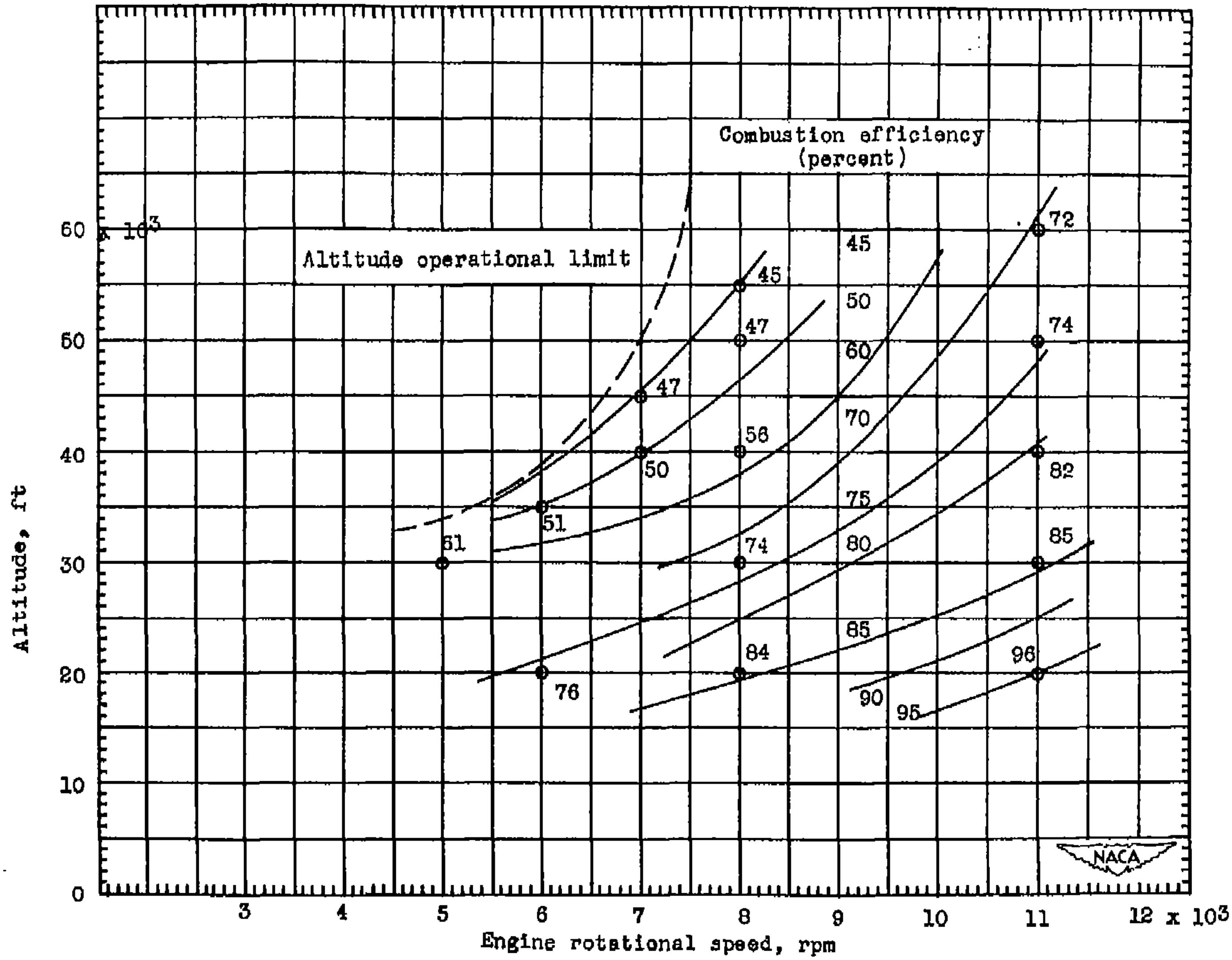
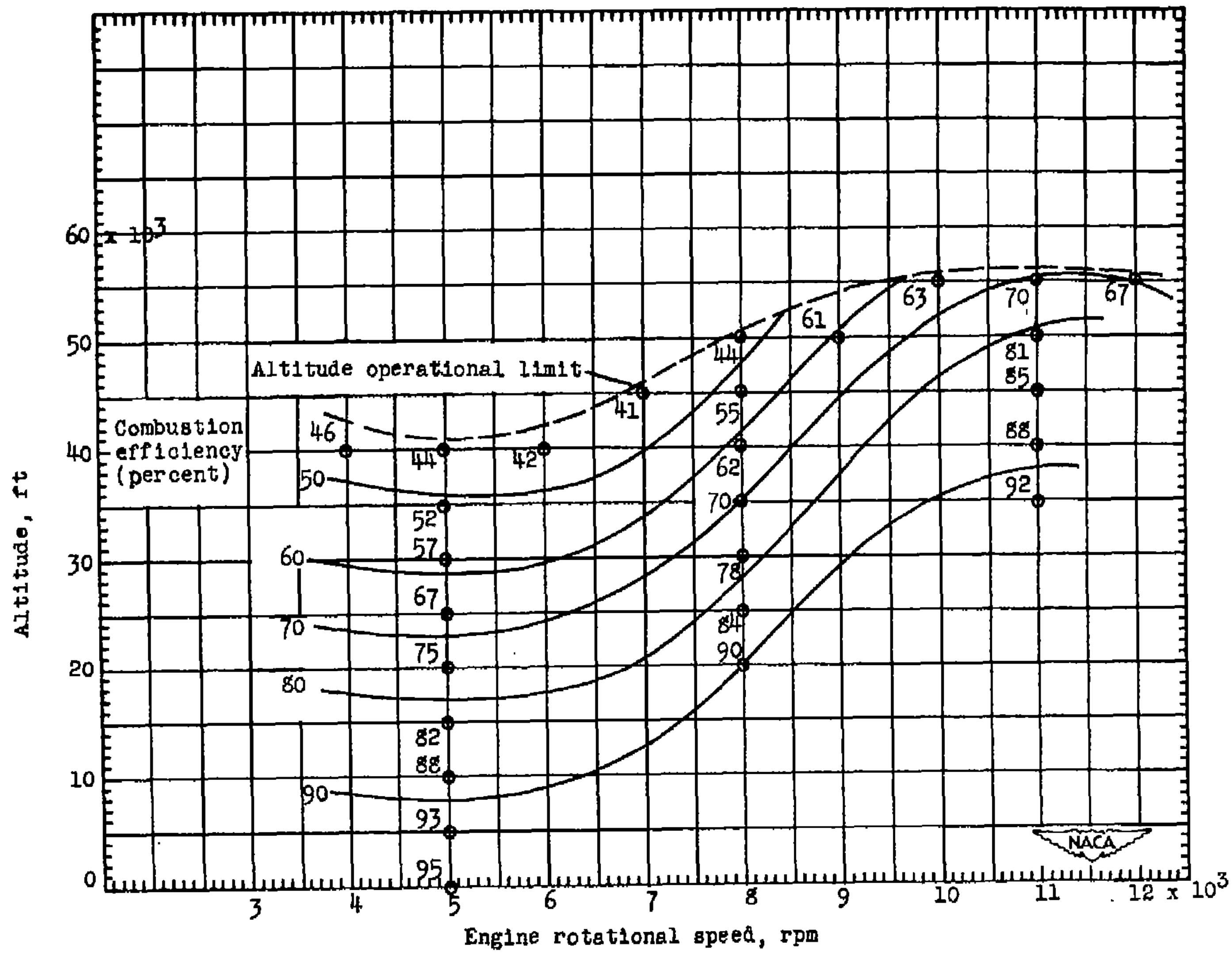


Figure 10. – Comparison of altitude operational limits of combustors with air flows based on included areas.



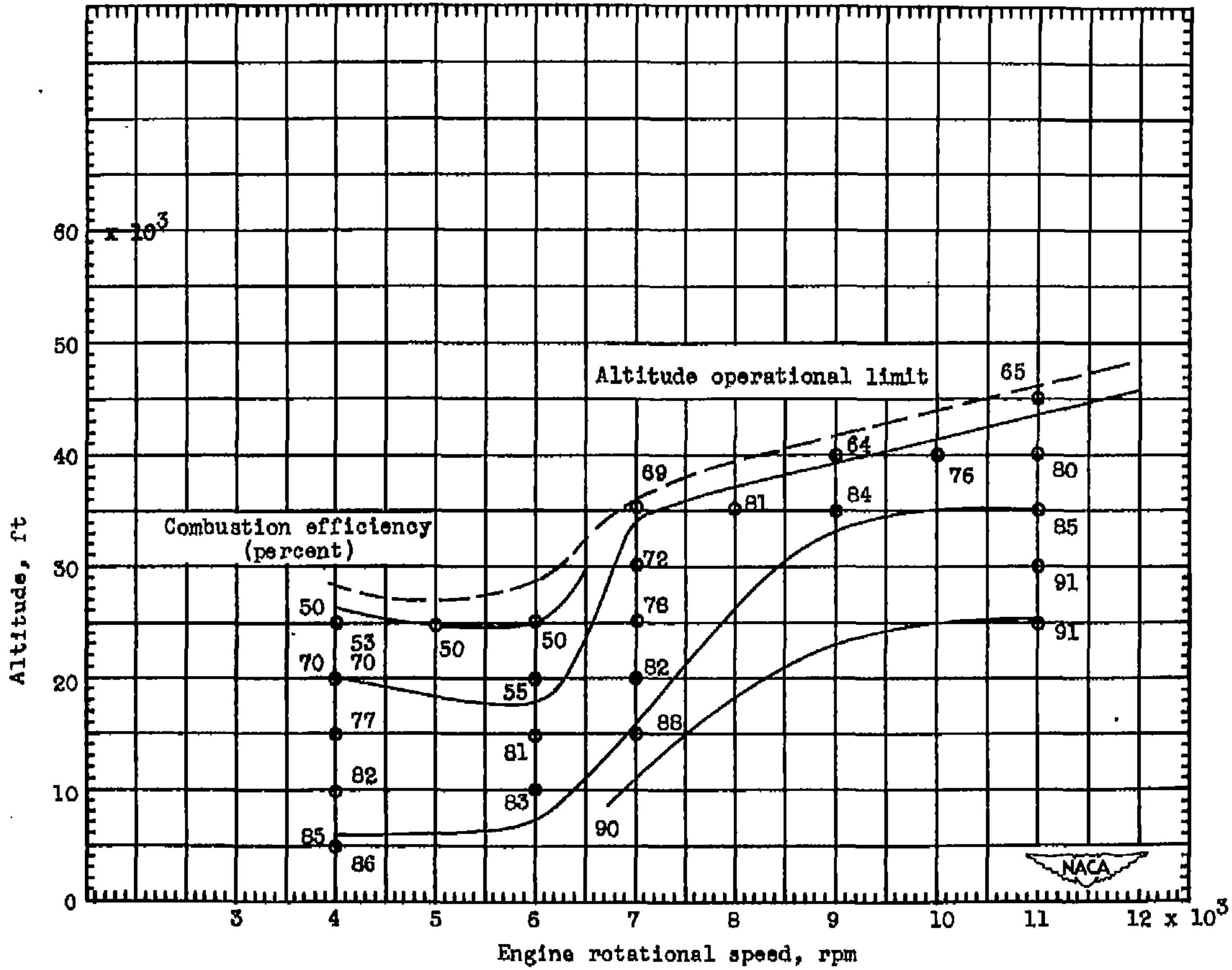
(a) U. S. can type.

Figure 11. - Combustion efficiency at various simulated operating conditions of reference engine for air flows based on actual maximum cross-sectional area.



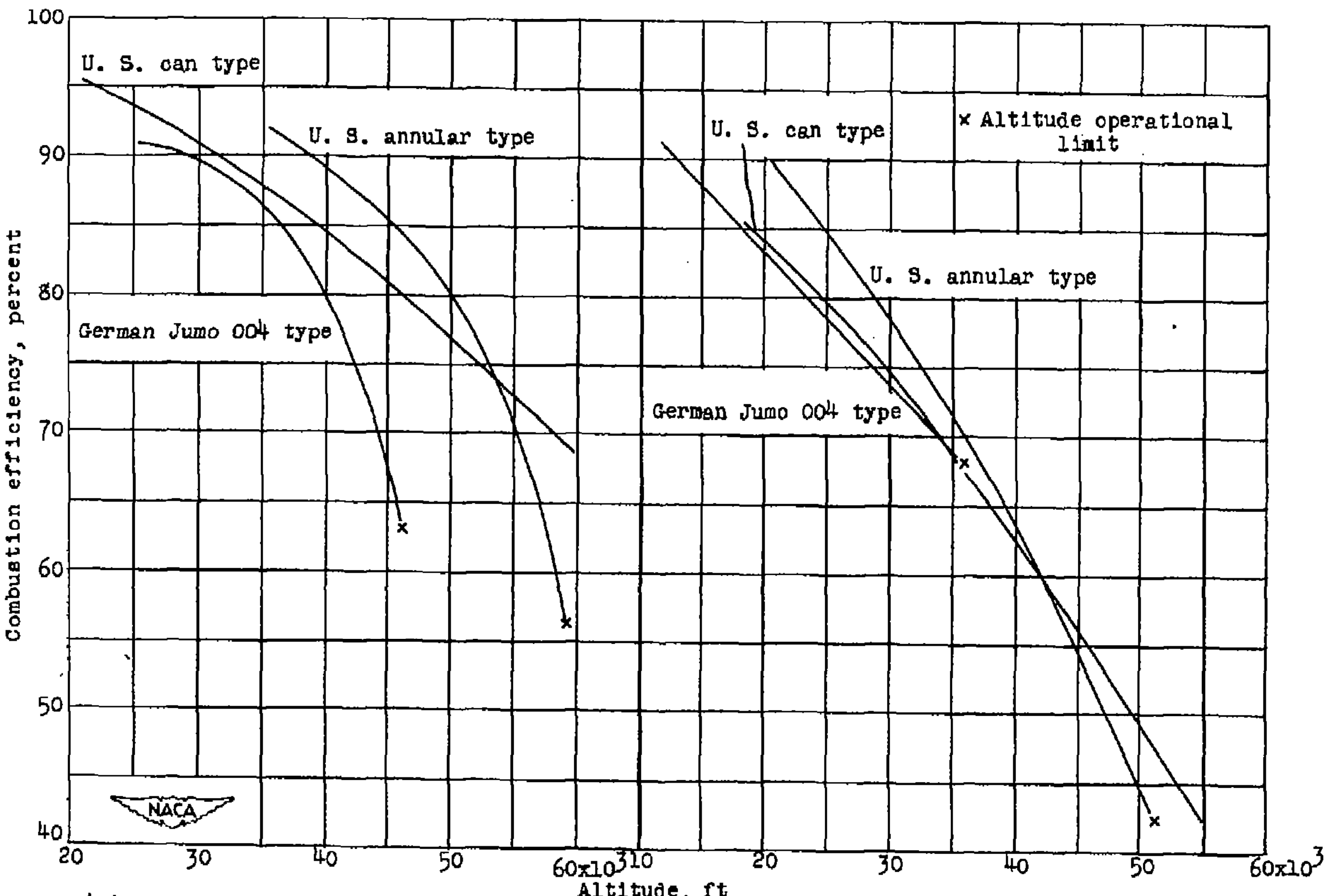
(b) U. S. annular type.

Figure 11. - Continued. Combustion efficiency at various simulated operating conditions of reference engine for air flows based on actual maximum cross-sectional area.



(c) German Jumo 004 type.

Figure 11. - Concluded. Combustion efficiency at various simulated operating conditions of reference engine for air flows based on actual maximum cross-sectional area.



(a) Engine rotational speed, 11,000 rpm.

(b) Engine rotational speed: U. S. combustors, 8000 rpm; German Jumo 004, 7000 rpm.

Figure 12. - Variation of combustion efficiency with altitude for air flows based on actual maximum cross-sectional areas.

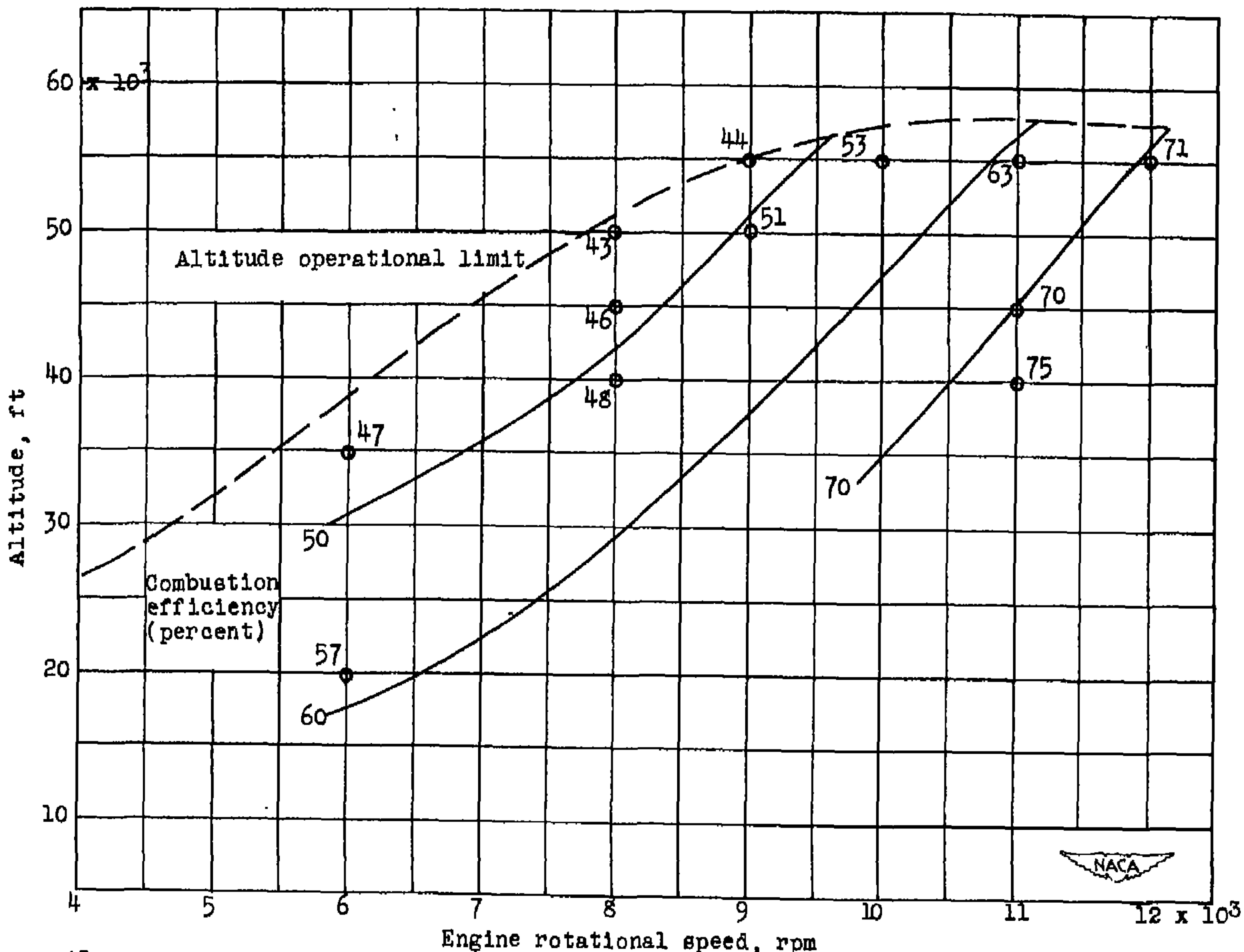
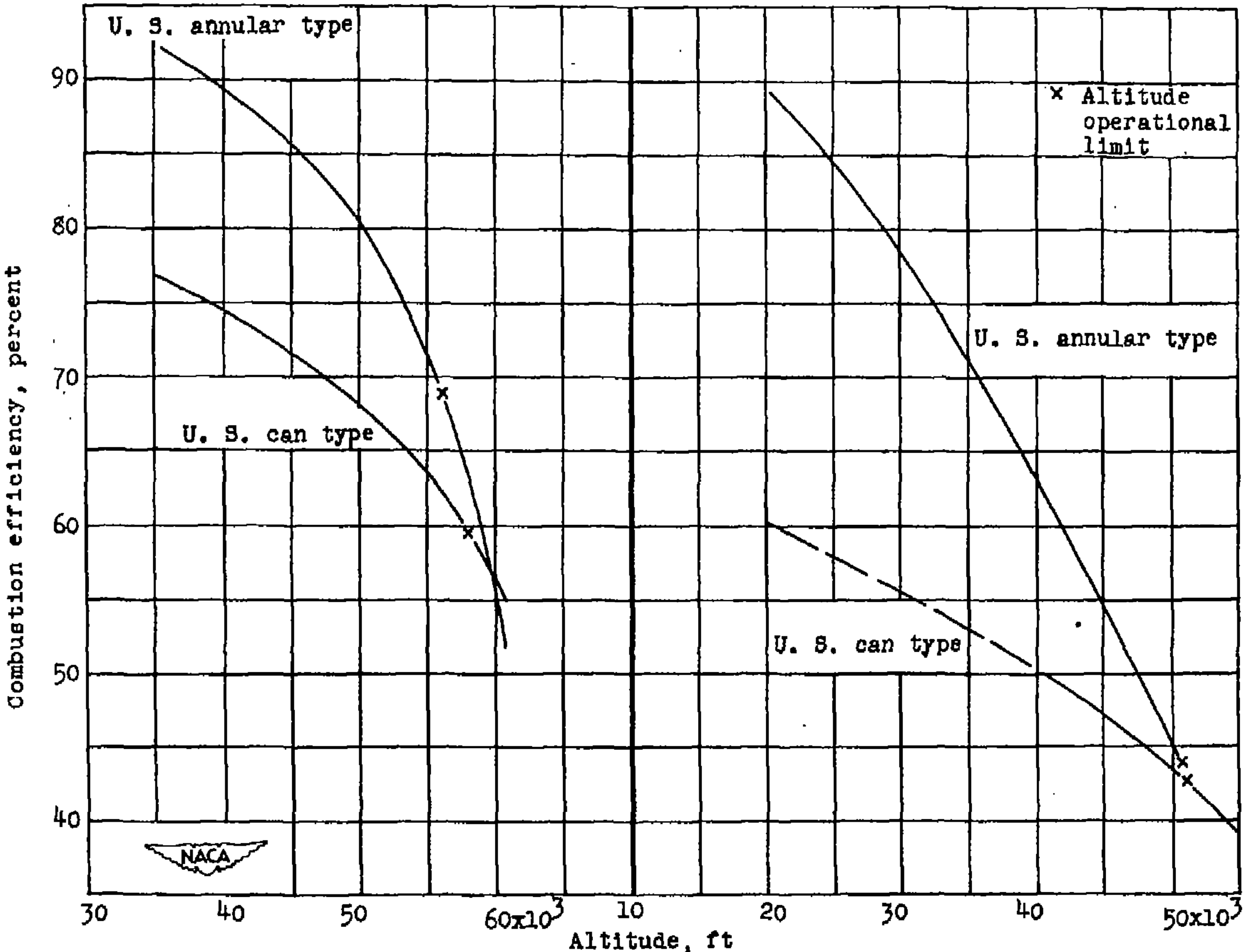


Figure 13. - Combustion efficiency at various simulated operating conditions of reference engine for U. S. can-type combustor; air flows based on included annular area.



(a) Engine rotational speed, 11,000 rpm.   (b) Engine rotational speed, 8000 rpm.

Figure 14. - Variation of combustion efficiency with altitude for air flows based on included annular areas.

835

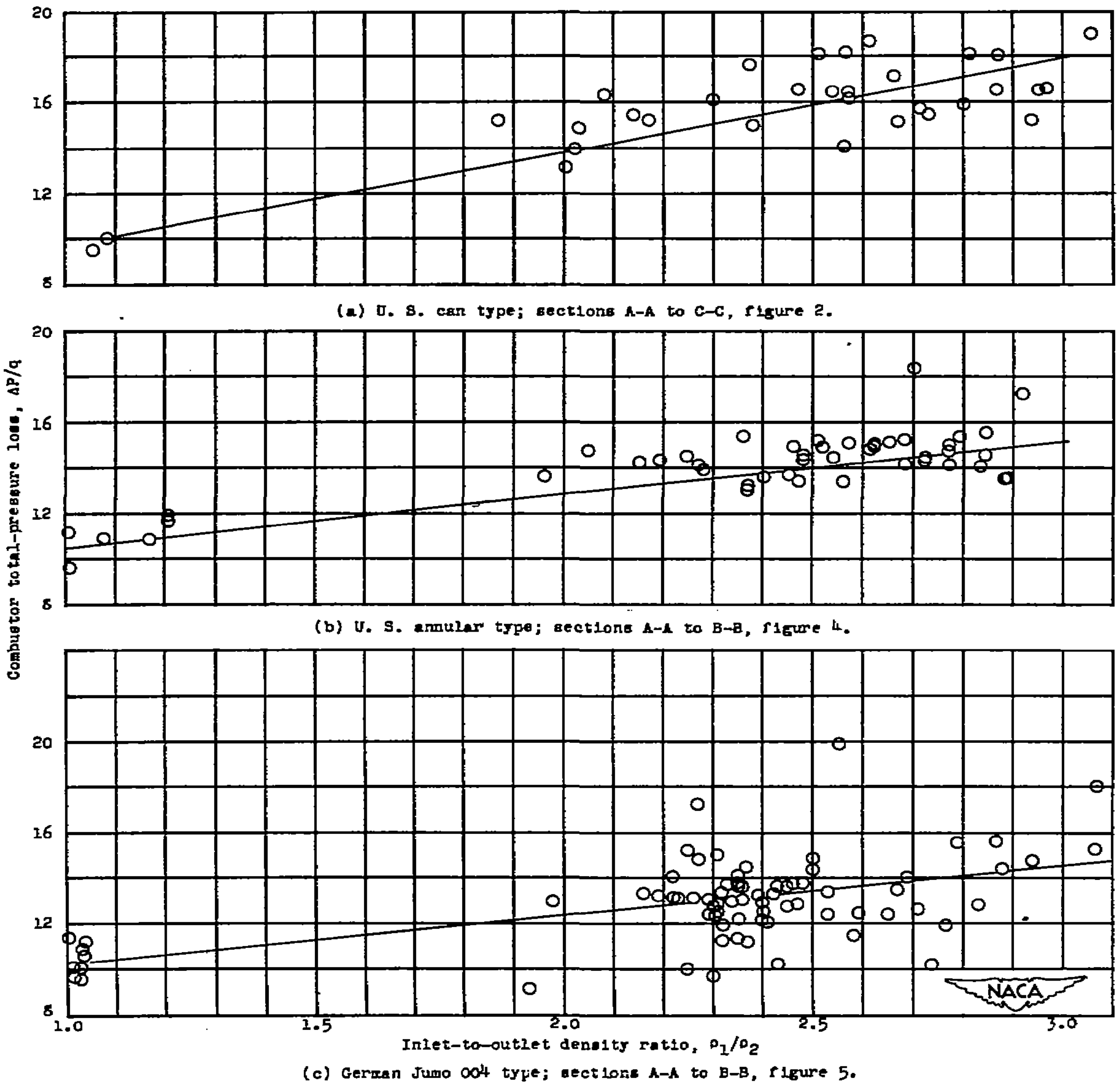
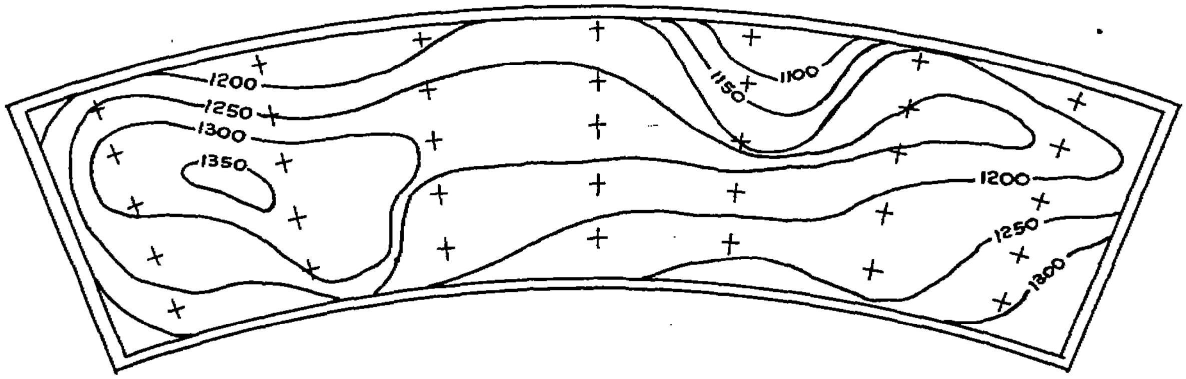
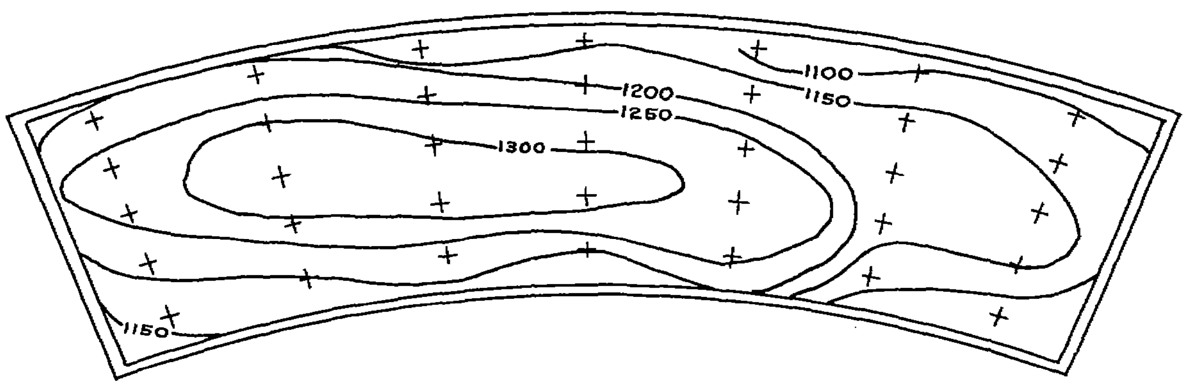


Figure 15. - Correlation of combustor inlet-to-outlet total-pressure-loss data.

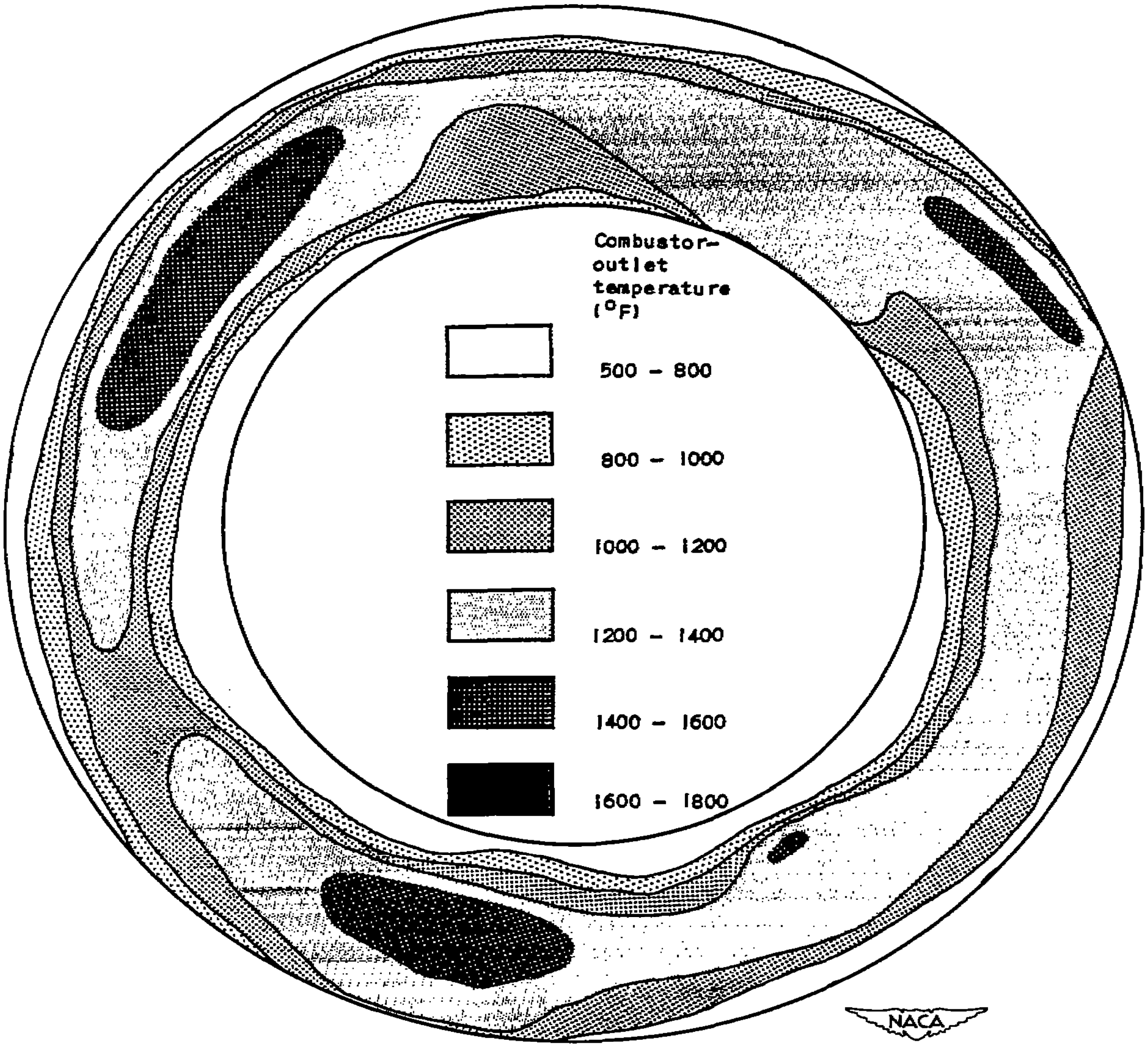


(a) Altitude, 20,000 feet.



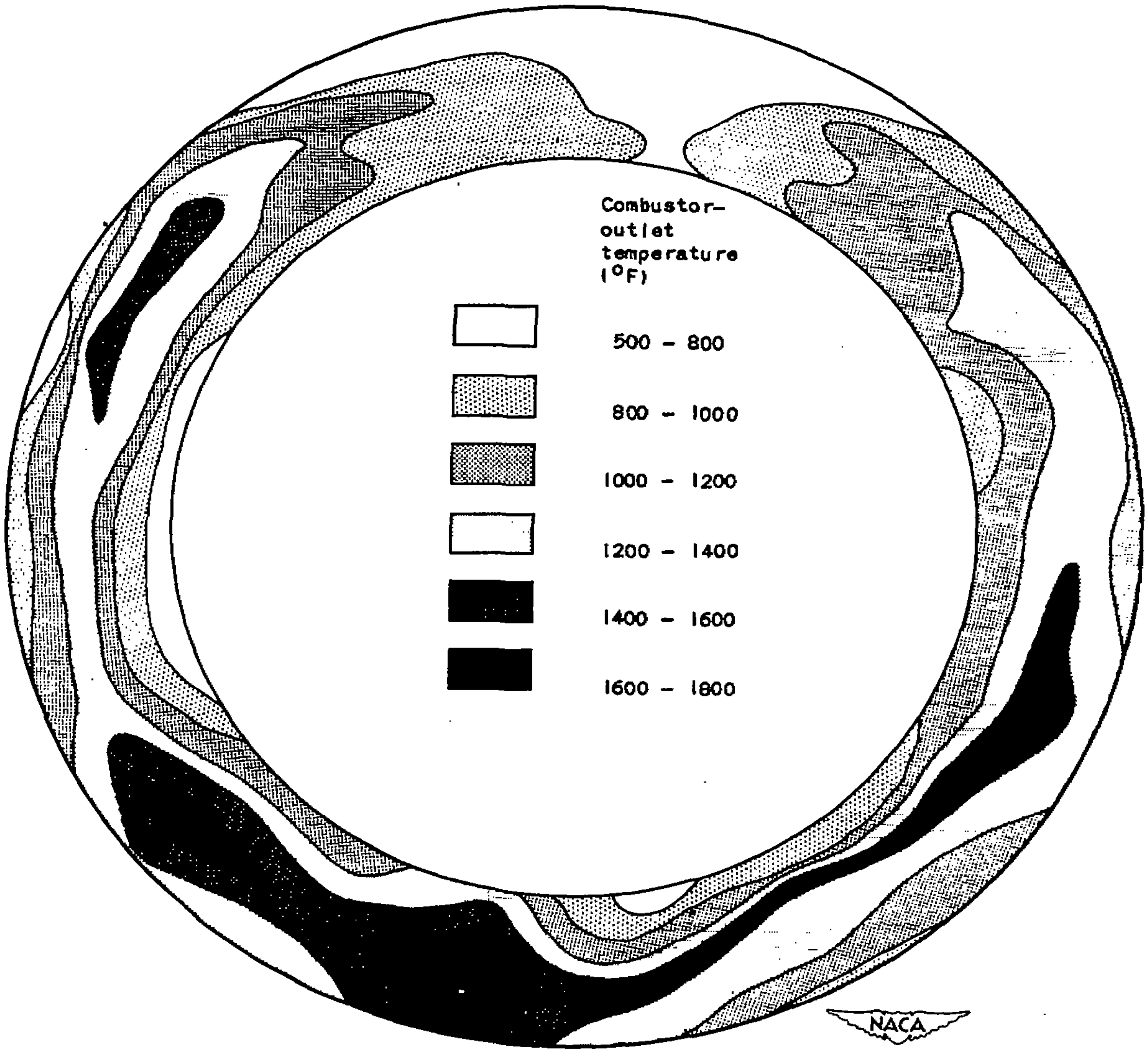
(b) Altitude, 60,000 feet.

Figure 16. - Temperature profiles of U. S. can-type combustor at combustor outlet for air flows based on actual maximum cross-sectional area. Engine speed, 11,000 rpm. (Temperatures in °F.)



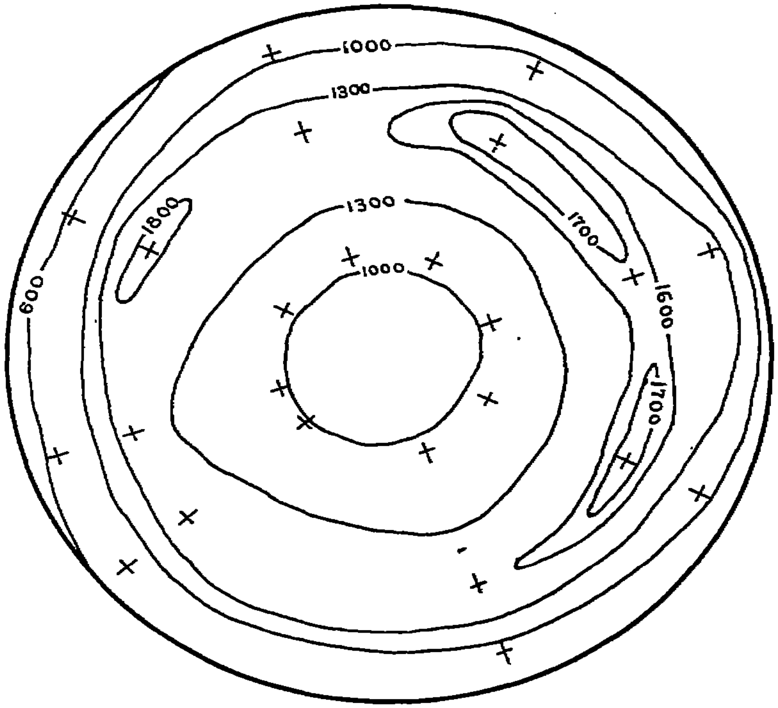
(a) Altitude, 35,000 feet.

Figure 17. - Temperature profile of U. S. annular-type combustor at combustor outlet for air flows based on actual maximum cross-sectional area. Engine speed, 11,000 rpm.

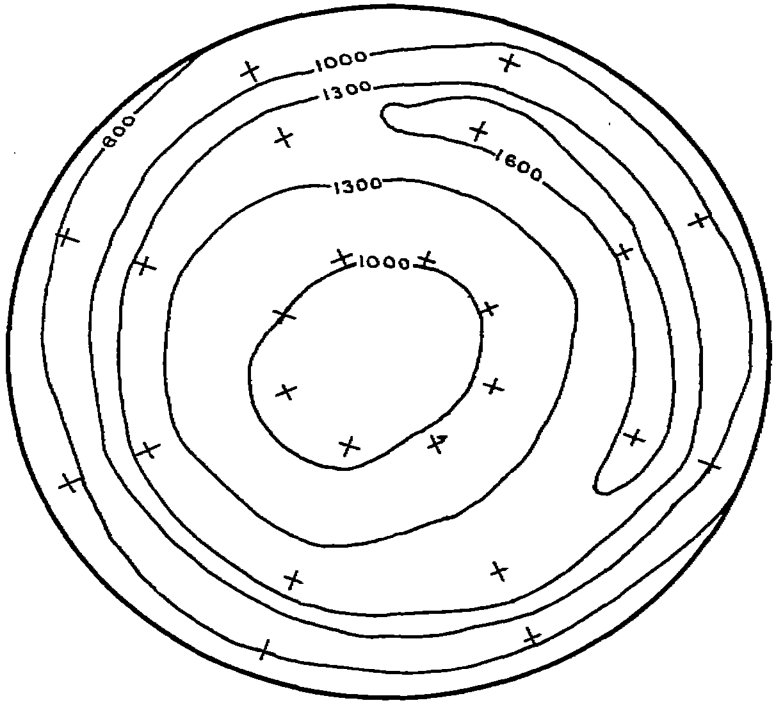


(b) Altitude, 55,000 feet.

Figure 17. - Concluded. Temperature profile of U. S. annular-type combustor at combustor outlet for air flows based on actual maximum cross-sectional area. Engine speed, 11,000 rpm.

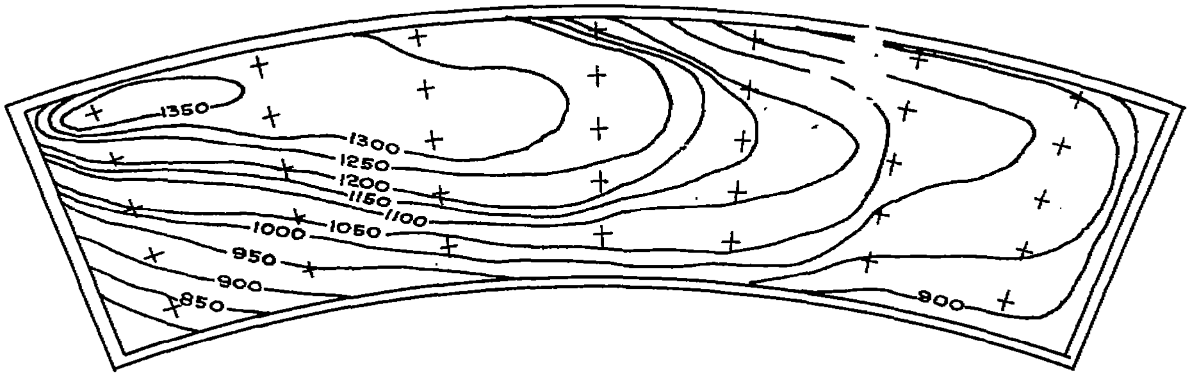


(a) Altitude, 25,000 feet.

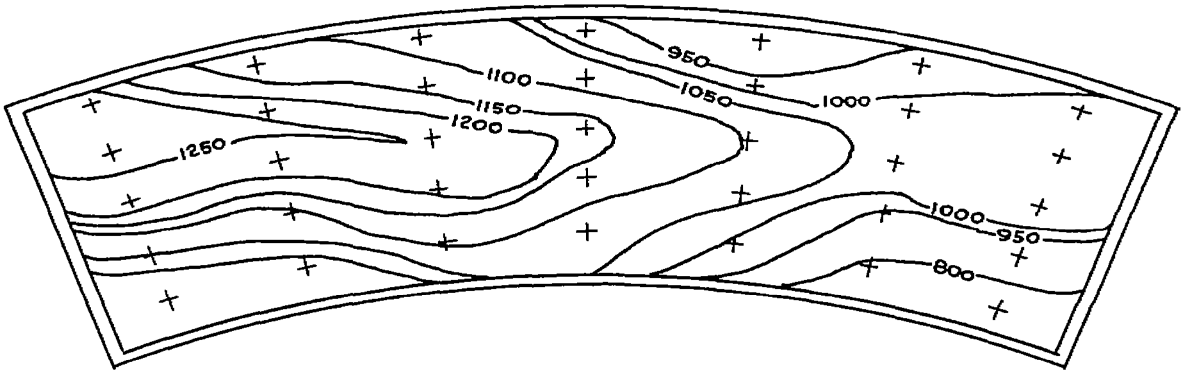


(b) Altitude, 40,000 feet.

Figure 18. - Temperature profiles of German Jumo 004 combustor at combustor outlet for air flows based on actual maximum cross-sectional area. Engine speed, 11,000 rpm. (Temperatures in °F.)



(a) Altitude, 45,000 feet.



(b) Altitude, 60,000 feet.

Figure 19. - Temperature profiles of U. S. can-type combustor at combustor outlet for air flows based on included annular area. Engine speed, 11,000 rpm. (Temperatures in °F.)